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Fabrication of blue and green non-polar InGaN/GaN multiple quantum well light-emitting diodes on $LiAlO_2(100)$ substrates

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The non-polar m-plane InGaN/GaN light-emitting diodes (LEDs) grown by metal-organic chemical vapor deposition (MOCVD) on $LiAlO_2(100)$ substrates were investigated. The structure of LEDs is composed by GaN p–n junction and five InGaN/GaN multiple quantum wells (MQWs). They emit blue or green light, respectively, with different indium composition of InGaN as active layers in the MQWs. Third-order satellite peaks are observed in high resolution X-ray diffraction spectrum, indicating good quantum well interfaces. For $800 \times 800\,\mu m^2$ blue LED device, the output power achieves 3 mW under 200 mA injection current. The electroluminescence (EL) spectra of both non-polar blue and green InGaN/GaN LEDs show that the EL peak wavelength of LEDs almost saturates at certain position with increasing injection currents. This proves the absence of polarization fields in the active region present in c-plane structures.

1 Introduction III-nitride materials provide great practical benefits in producing short wavelength light-emitting diodes (LEDs) and laser diodes (LDs). Spontaneous and piezoelectric polarization along the *c*-axis of wurtzite GaN and its alloys greatly affect the efficiency of luminescence in GaN-based optoelectronic devices. The quantum efficiency decreases due to the spatial separation of the electron and hole wave functions within the quantum wells (QWs). In order to eliminate these polarization effects, one alternative way is to grow non-polar [$(1\bar{1}00)$ and $(11\bar{2}0)$] or semipolar GaN thin films and InGaN/GaN QWs along unconventional non-*c*-axis directions. Since the development of non-polar m-plane GaN/AlGaN heterostructures on $LiAlO_2$ (LAO) by molecular beam epitaxy (MBE) [1], some developments have been made in fabrication of non-polar LEDs on r-plane sapphire [2, 3] or LAO substrates [4, 5]. Recently, high brightness non-polar LEDs had been obtained on bulk GaN substrates [6]. And efficient semipolar $(11\bar{2}2)$ amber or yellow LEDs were also fabricated, whose performance is prior to the commercially available AlInGaP LEDs [7]. In this paper, we report the growth of non-polar m-plane InGaN/GaN multiple quantum wells (MQWs) structure by metal-organic chemical vapor deposition (MOCVD), and fabrication of blue and green LEDs on LAO(100) substrates.

2 Experimental The $In_xGa_{1-x}N$/GaN LED structures, as shown in Fig. 1, were grown on LAO(100) using a Thomas Swan MOCVD system which has a close-coupled-showerhead reactor. Trimethylgallium (TMGa), trimethylindium (TMIn), and ammonia (NH_3) were used as the precursors for In, Ga, and N, respectively. Silane (SiH_4) and bis(cyclopentadieny)magnesium (Cp_2Mg) were used for n- and p-type dopings. To protect the LAO substrate surface against reacting with hydrogen (H_2) initially, a 200 nm-thick cover buffer layer of GaN was grown at 850 °C [8]. Then the reactor temperature was ramped to 1020 °C for growing the main GaN layer. After grown a 1 μm-thickness Si-doped n-type with concentration of $1 \times 10^{19}\,cm^{-3}$, the active region consisted of a five period MQWs. The In composition x of $In_xGa_{1-x}N$ in well layers was from 0.2 to 0.3 in order to adjust emitting light wavelength of the QWs. At last, a 150 nm Mg-doped p-type GaN layer ($p \sim 10^{17}\,cm^{-3}$) and

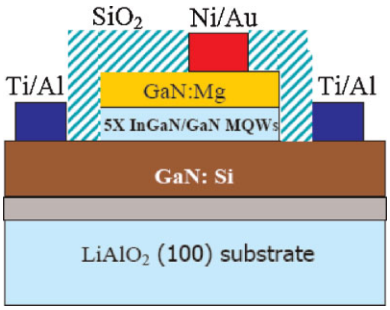

Figure 1 (online color at: www.pss-a.com) Schematic illustration of the non-polar m-plane InGaN/GaN MQW LED structure on $LiAlO_2$(100).

a 30 nm p^+-GaN layer was grown. 200 μm × 200 μm, 400 μm × 400 μm, and 800 μm × 800 μm rectangular mesa devices were fabricated using reactive ion etching to access the bottom n-GaN. SiO_2 was used as passivation layer. Ti (500 Å)/Al(3000 Å) and Ni(500 Å)/Au(3000 Å) were used as n- and p-contact metals, respectively. The crystalline properties of m-plane blue InGaN/GaN MQWs LED structure were probed by PANalytical X'pert MRD triple-axis X-ray diffraction (XRD). The electroluminescence (EL) spectra of m-plane blue and green LEDs under different injection currents were measured at room temperature (RT). And the light output power of blue LEDs was collected by integrating spheres of diameter 150 mm.

3 Results and discussion Figure 2 shows the triple-axis $\omega-2\theta$ scan of an m-plane InGaN/GaN MQWs green LED structure on LAO(100) substrate. As shown the measured spectrum, it is observed that the strongest peak is correspond to the $(1\bar{1}00)$ diffraction of GaN:Si layer. On the left of the peak, a shoulder peak is found, which origins from the InGaN alloy diffraction in the MQWs. In addition, at least third-order satellite peaks are observed, which indicates the good interfaces of MQWs. The period P of QW is given by:

$$P = \frac{\lambda}{2(\sin\theta_m - \sin\theta_{m-1})}$$

where λ is the wavelength of Cu $K\alpha_1$ radiation. θ_m and θ_{m-1} are the angular positions of two successive satellites. And the average alloy content $\bar{x}$ of the structure is given by the angular position of the zeroth-order satellite SL0 [9]. The XRD spectrum of blue LED structure has higher angular position of the zeroth-order satellite SL0 compared than green LED, which indicates the average alloy In content is lower than green LED structure. The determination of the individual layer thicknesses of well and barrier, the actual alloy content x of the ternary InGaN is implemented by PANalytical X'Pert EPITAXY 4 soft package using kinematical analysis. An automated simulation routine achieves excellent agreement with the experimental data, as shown in Fig. 2 with red line. The best fit parameters returned from the simulation are 1.9 nm $In_{0.29}Ga_{0.71}N$ wells and 21.6 nm GaN barriers.

Figure 3a and b shows the EL spectra of two m-plane InGaN/GaN LEDs under different injection currents. All the EL spectra were measured under dc bias at RT. They emit

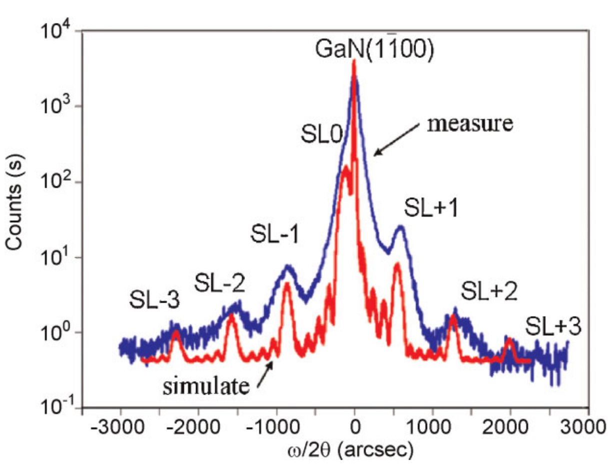

Figure 2 (online color at: www.pss-a.com) Measured and simulated XRD spectra of a non-polar m-plane InGaN/GaN MQW green LED structure.

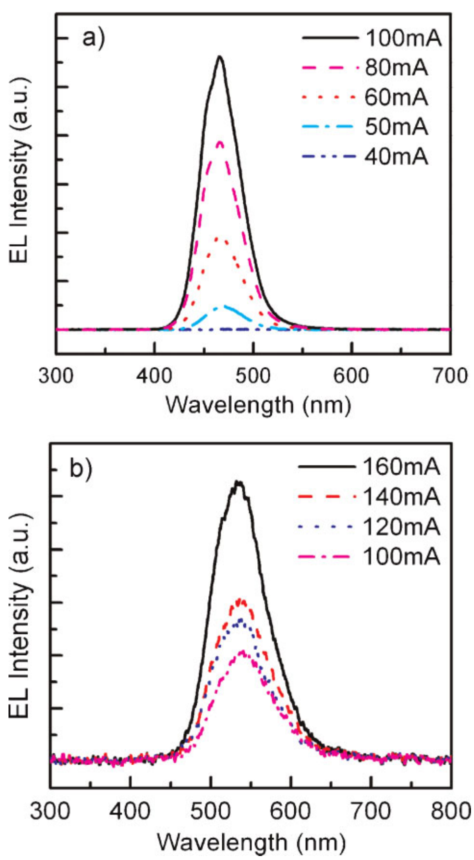

Figure 3 (online color at: www.pss-a.com) (a) The EL spectra of blue LEDs and (b) the EL spectra of green LEDs under different injection currents.

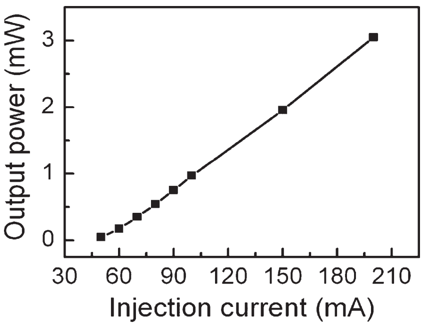

Figure 4 Dependence of output power on DC drive current for the m-plane blue LED.

blue light at around 465 nm (Fig. 3a) and green light (Fig. 3b) at around 535 nm, respectively. As shown, both blue and green non-polar LEDs exhibit much smaller blueshift with increasing injection currents compared than the *c*-axis polar LEDs. The green LED exhibits blue shift of 5 nm and the blue LED exhibits 7 nm, which is attributed to the band filling of the localized states induced by alloy fluctuation in InGaN QWs. It is consistent with the results reported [2, 3, 10]. Thus we concluded that it is absence of polarization fields in the active region. Furthermore, it is noticed that the threshold current of non-polar LEDs is higher than commercially c-plane GaN-based LEDs. It is proved by *I–V* characteristics that there exists a shunt resistor parallel to the p–n junction caused by non-radiative centers in the MQWs active region. When these centers are saturated, a linear relation between EL intensity and injection current holds and nearly every injected carrier leads to the emission of a photon [4].

Figure 4 presents the dependence of output power measured in an integrating sphere on a DC driving current for an $800 \times 800\ \mu m^2$ blue LED. There was no indication of ''roll-off'' of the output power with the increase in drive current. Under higher injection current (>150 mA), the heat dissipation seems not good because of comparatively poor thermal conductivity of LAO substrate and produced large leakage current. The output power of blue non-polar LEDs achieves 3.05 mW, and corresponding to external quantum efficiency (EQE) of 0.28%. However, the EQE value of blue LEDs on LAO is lower than these on bulk GaN reported by Lin et al. [10] recently, it is the report that fabrication of non-polar LEDs on LAO substrates with microwatt output.

4 Summary We have investigated the growth and fabrication of non-polar blue and green InGaN/GaN LEDs on LAO(100) substrates. Third-order satellite peaks are observed in high resolution XRD spectrum, indicating good QW interfaces. For $800 \times 800\ \mu m^2$ blue LED device, the output power achieves 3.05 mW under 200 mA injection current. The EL spectra of non-polar blue and green InGaN/GaN LEDs show the peak wavelength of LEDs almost saturates at certain position with increasing injection currents. This proves the absence of polarization fields in the active region present in c-plane structures.

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